Comparison of Total Ionizing Doses from Representative Space Radiation Shielding Analysis Tools

Bongim Jun*, Luz Maria Martinez Sierra, Brian X. Zhu, and Insoo Jun

Outline

- Motivation
- Introduction to Transport Tools Evaluated in This Study
- NOVICE Validation Against MCNP
  - Why do you believe that NOVICE is “conservative”
  - Verification that NOVICE is being used properly
- FASTRAD Validation Against NOVICE
  - Shielding Geometries and Mission Environment
  - Simple Geometry (Shell and Box)
  - Cylindrical Vault Geometry
  - Complex Geometries
- Geant4 Validation Against MCNP
  - Forward Monte Carlo Results from Geant4, FASTRAD, and MCNP
- Conclusion

Motivation

- Space radiation is a key design consideration for any space mission
- Spacecraft should be designed to survive exposure to expected radiation environment for a mission
- Multiple commercial tools are available to predict ionizing and displacement damage doses, but they often produce differing results beyond stated errors
- Good understanding of dose predictability of transport tools is critical for shielding design optimization

Introduction to Transport Codes

FASTRAD

- **Purpose:** system-level TID calculations and shielding analysis for parts/materials
- **Method: Ray tracing** (Input requirement: Dose Depth curves from e.g. Shieldose, NOVICE)
- **CAD input:** STEP, IGES, GDML format
- **Run Time:** Quick running time (minutes to hours)

NOVICE

- **Purpose:** system-level TID calculations and shielding analysis for parts/materials
- **Method: Adjoint Monte Carlo method** (reverse Monte Carlo, RMC)
- **CAD input:** VRML format
- **Run Time:** Moderate running time (hours to days)

Geant4

- **Purpose:** detailed treatment of particle interaction physics for part/material/detector response simulation.
- **Method: Forward Monte Carlo (FMC) particle transport** with accurate physics and data bases for nuclear interactions
- **CAD input:** CSG, GDML format
- **Run Time:** Moderate running time (hours to days)

MCNPX

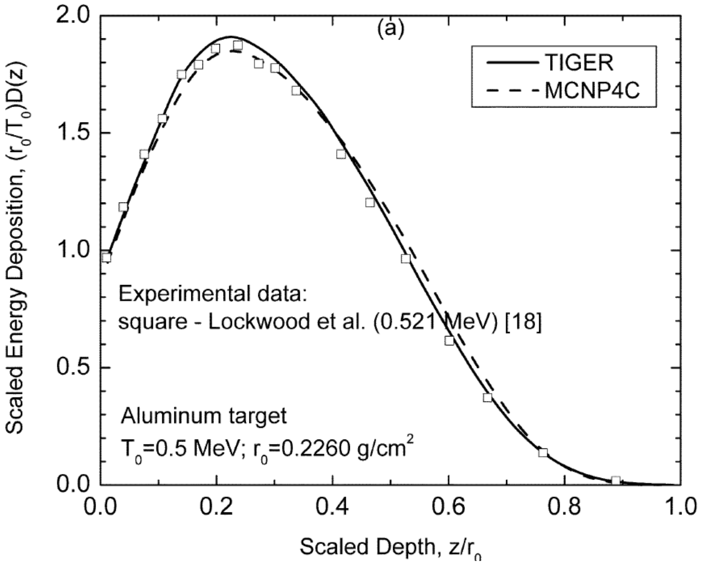
- **Purpose:** detailed treatment of particle interaction physics for part/material/detector response simulation.
- **Method: Forward Monte Carlo particle transport** with accurate physics and data bases for nuclear interactions
- **CAD input:** No direct transport format available. Not for S/C level analysis
- **Run Time:** Long running time (days)

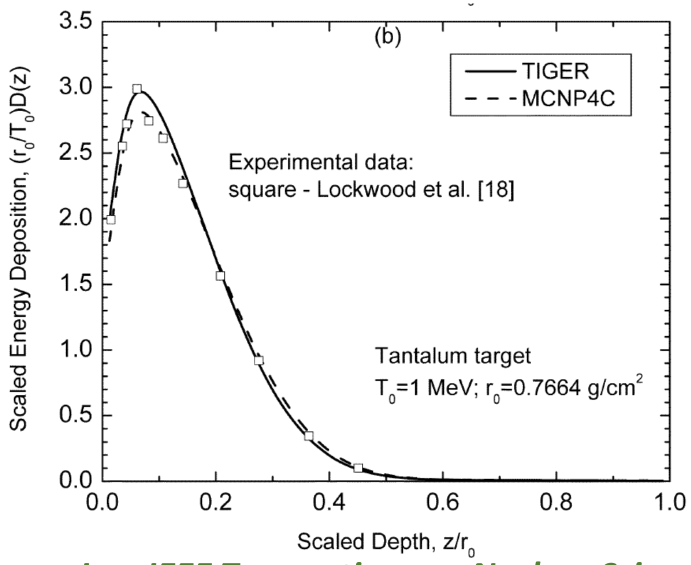
LONGER Running Time

NOVICE Validation: [1/2]

Is MCNP Acceptable?

- MCNP Analysis:
  - Forward Monte Carlo particle transport with accurate physics and data bases for nuclear interactions
  - MCNP's dose predictability has been demonstrated through numerous ground experiments with wide ranges of materials and energies





- Insoo Jun, IEEE Transactions on Nuclear Science 2003

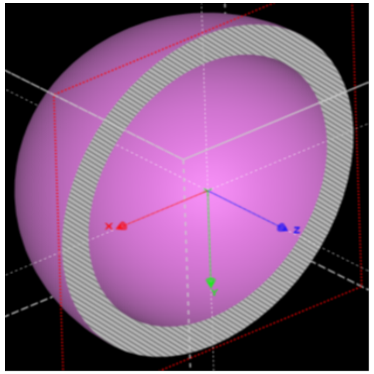
- *MCNP simulation results show good agreement with experiment results*

NOVICE Validation: [2/2]

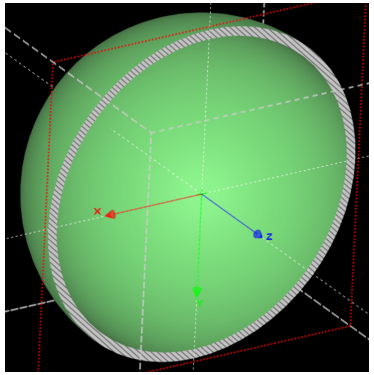
Is NOVICE Comparable to MCNP?

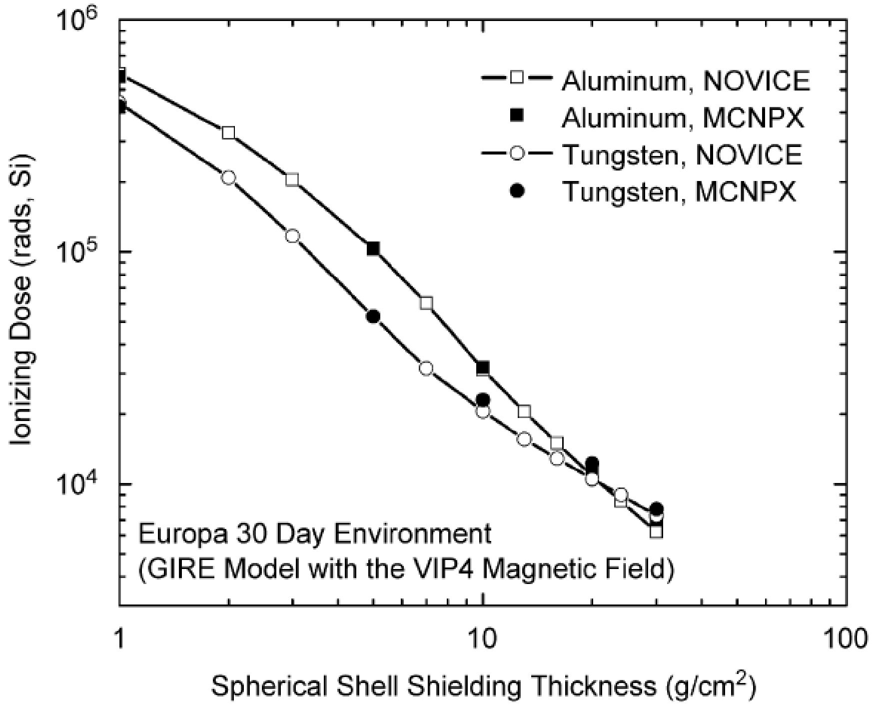
- TID comparison between MCNP and NOVICE
  - MCNPX
  - NOVICE 2006, adjoint b=4

Aluminum: 1 ~ 30 g/cm^2



Tungsten: 1 ~ 30 g/cm^2





-M. Cherng et al., Nuclear Instruments and Methods in Physics Research 2007

- *NOVICE results show good agreement with MCNP results*

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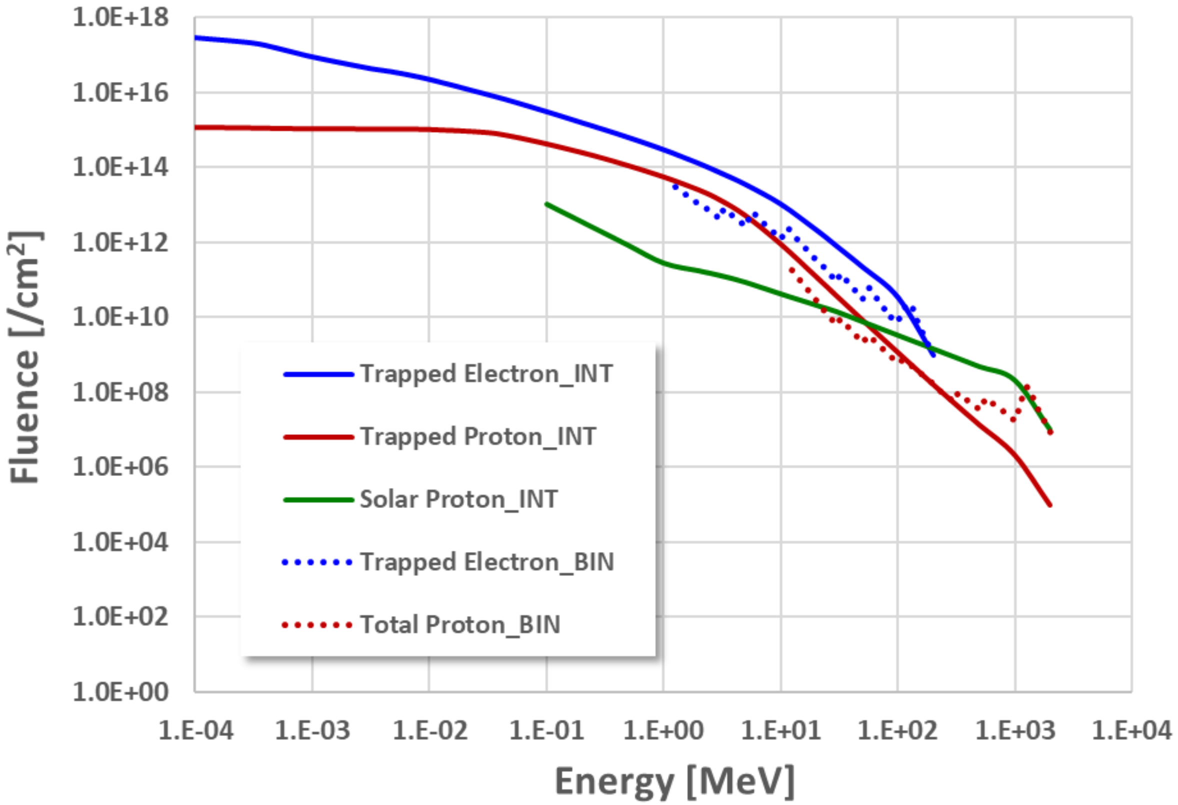
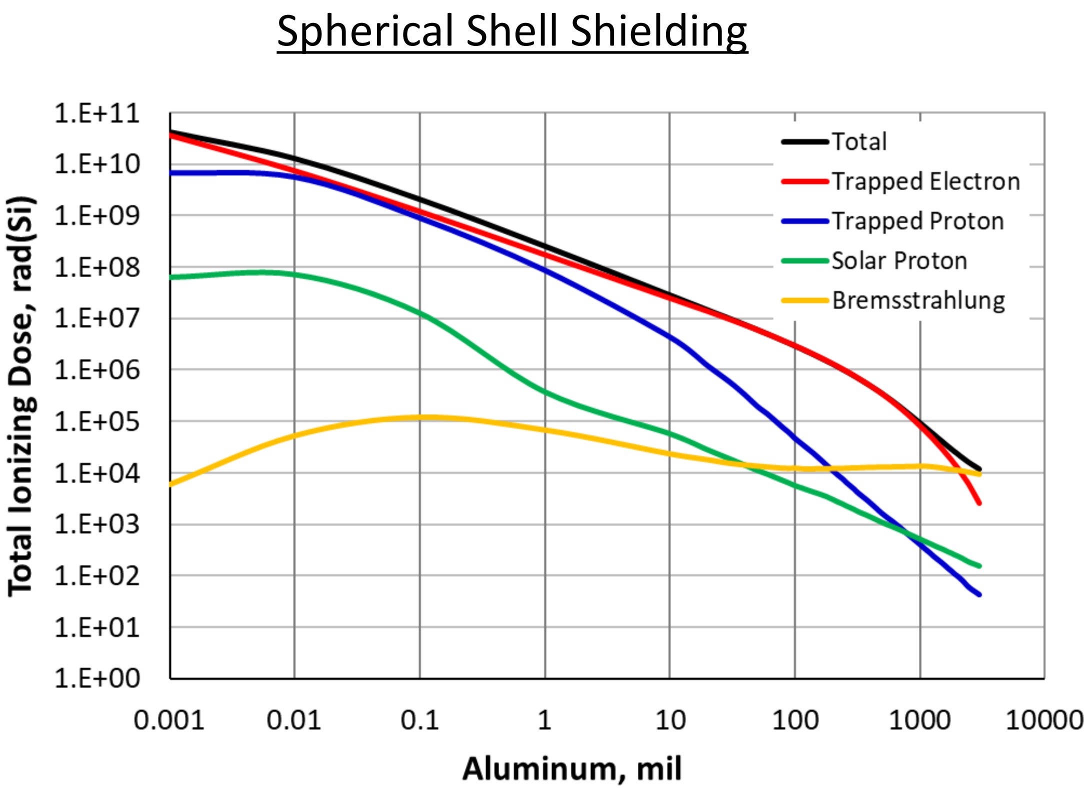
Mission Environment: Radiation Spectrum

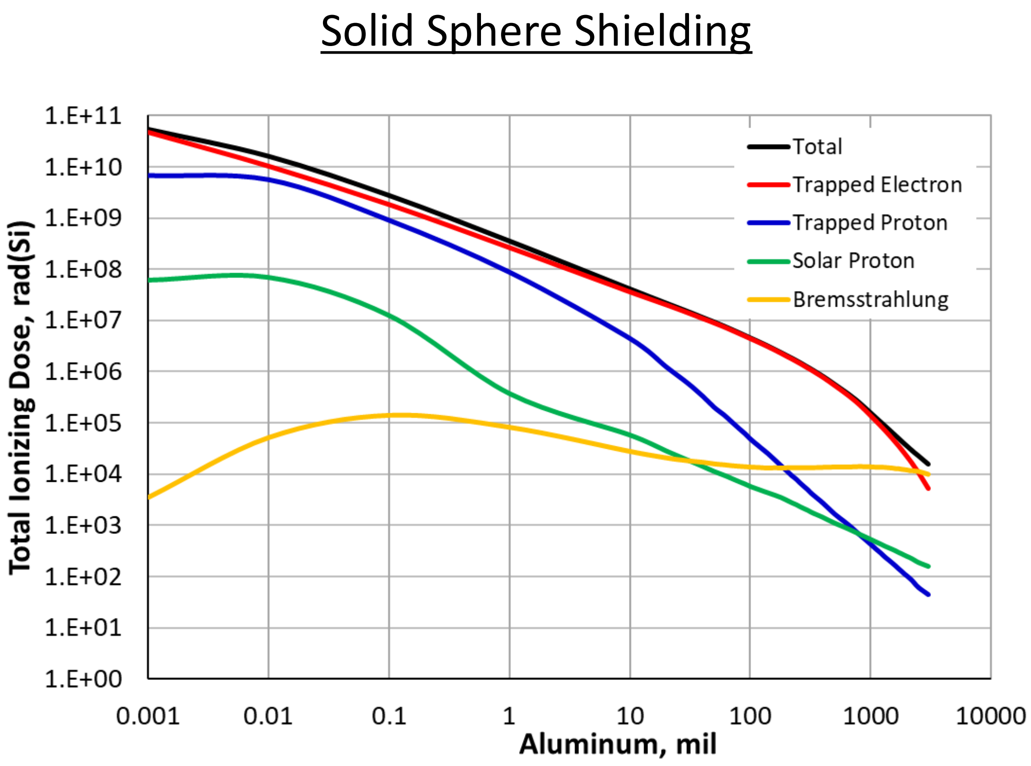
A Jovian Mission



- Intense radiation environment, dominated by trapped electrons
- All fluence spectra are input parameters in Monte Carlo code based tools

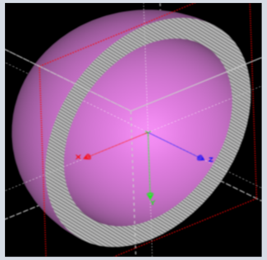
Ionizing Dose Depth Curves
Aluminum

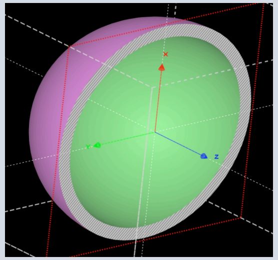


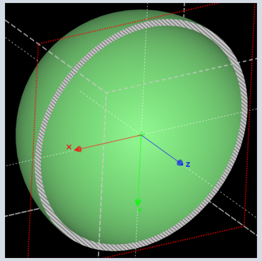


- NOVICE adjoint k-option was used for a series of Al shielding thicknesses
- FASTRAD uses NOVICE outputs as inputs in ray tracing analysis

Shield Geometries Used in This Study


S-1


S-2

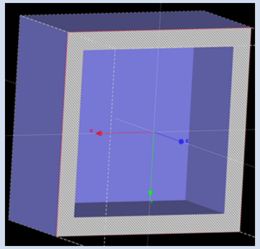

S-3

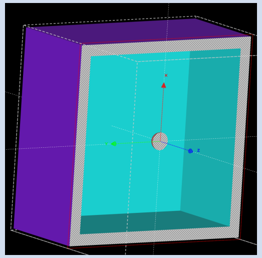
Spherical Shell

1. Material
   - S-1: Aluminum
   - S-2: Tantalum/Al
   - S-3: Ta
2. Dimension

Radius: 5 cm

Thickness: 0.05 ~ 30 g/cm^2


B-1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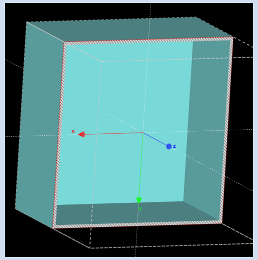
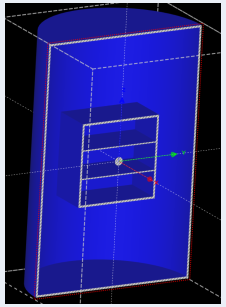

B-3

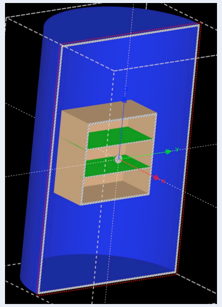
Cubic Box

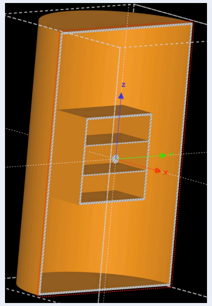
1. Material
   - B-1: Aluminum
   - B-2: Tantalum/Al
   - B-3: Ta
2. Dimension

Length: 10 cm

Thickness: 0.05 ~ 30 g/cm^2


C-1


C-2


C-3

Cylindrical vault

1. Material
   - C-1: Aluminum
   - C-2: PCB/Ta/Aluminum
   - C-3: Ta
2. Dimension

Cylinder (RxH)=10cm x30cm

Box/slab length= 10cm

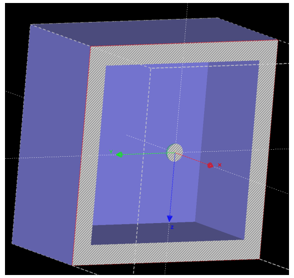
Thickness: 0.25 cm

- Shield Materials
  - Aluminum (d=2.7 g/cm^3)
  - Tantalum (d=16.6 g/cm^3)
  - Aluminum/Tantalum
- Transport Codes
  - MCNPX, MCNP6 FMC
  - FASTRAD 3.8.10
    - ray tracing, RMC, FMC
  - NOVICE 2017, adjoint b=8
  - Geant4, FMC
    - G4EmLivermorePhysics
    - G4HadronPhysicsQGSP_BIC_HP
- Point detector for ray tracing analysis
- Volume detector for Monte Carlo analysis
- Run errors of all remained less than 5%

FASTRAD Validation: [1/2]

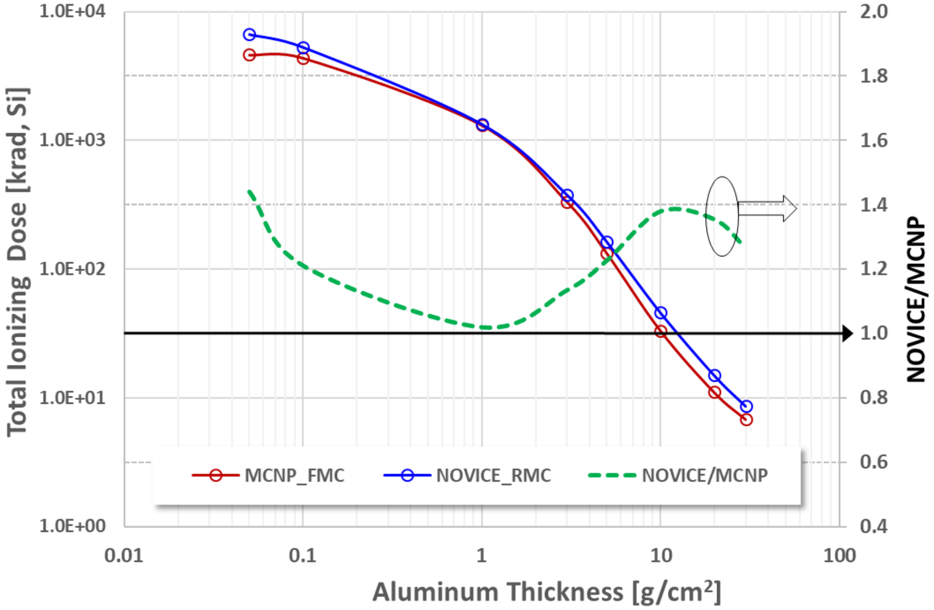
Is FASTRAD Conservative?

B-1

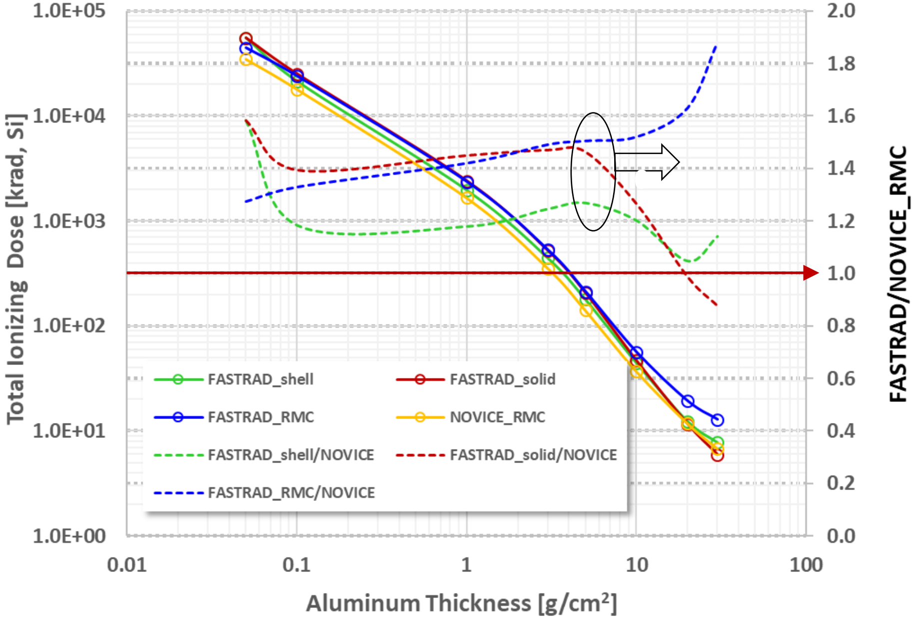


Al Thickness:
0.05 -30 g/cm²

MCNP vs. NOVICE



NOVICE vs. FASTRAD

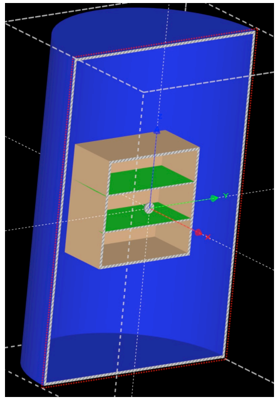


- NOVICE RMC, JPL heritage transport analysis tool, is conservative
- FASTRAD ray tracing over predicts doses in comparison with NOVICE
  - The discrepancy increases when high-Z material is incorporated (due to single material dose depth curves)
  - Shell shielding option shows better agreement with NOVICE for typical shielding thicknesses
- FASTRAD RMC predicts higher TID but the difference remains similar for high-Z shieldings

FASTRAD Validation: [2/2]

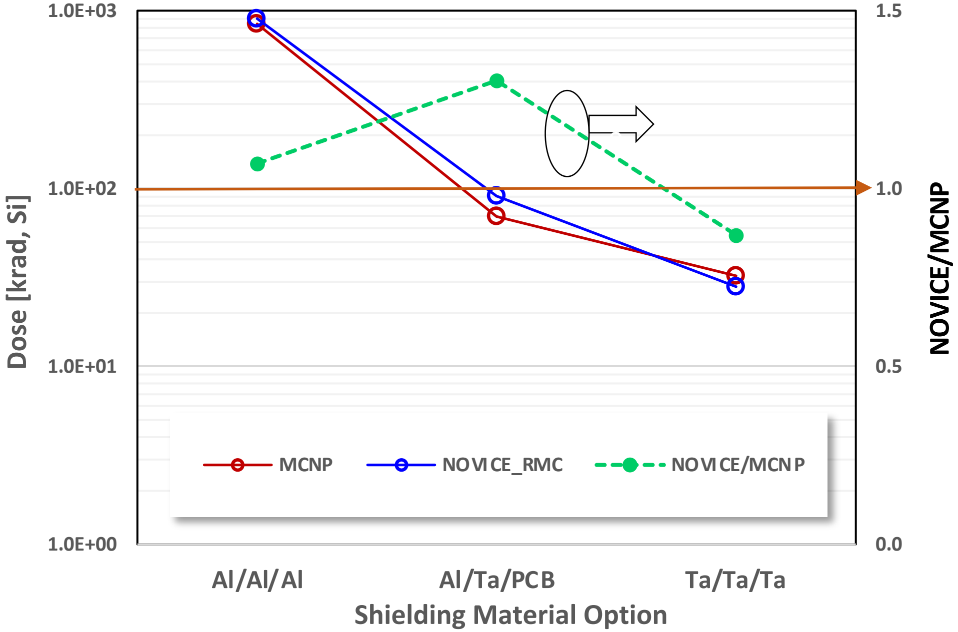
Is FASTRAD Too Conservative?

C-series

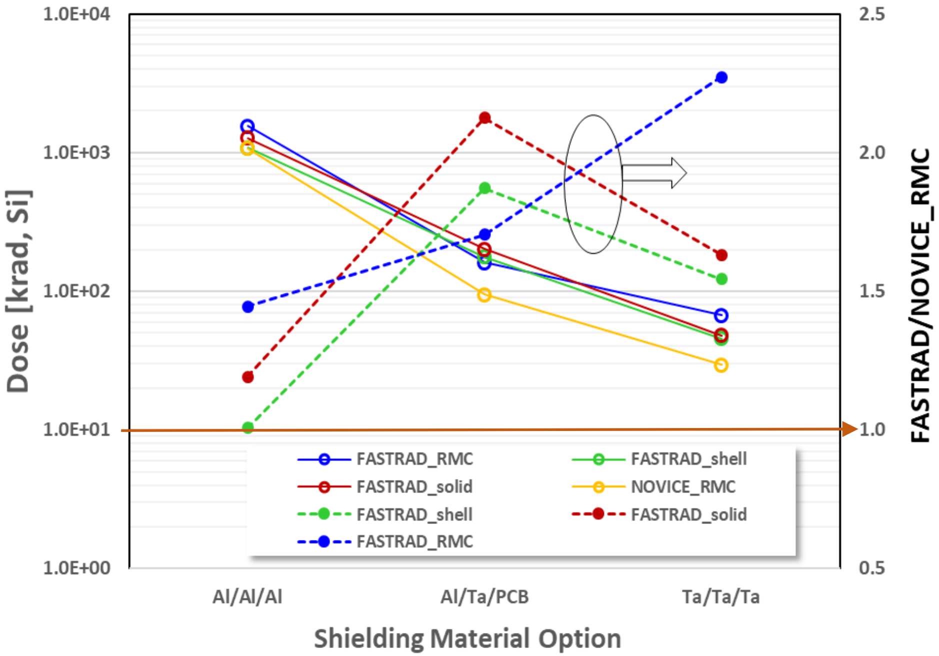


All aluminum
Al/Ta/PCB
All tantalum

MCNP vs. NOVICE



NOVICE vs. FASTRAD



- NOVICE RMC is conservative except high-Z, thick shielding geometry
- FASTRAD ray tracing predicts higher than NOVICE
  - Shell shielding option shows better agreement with NOVICE, especially for aluminum shielding geometry
- FASTRAD RMC predicts higher TID, especially when high-Z element is incorporated

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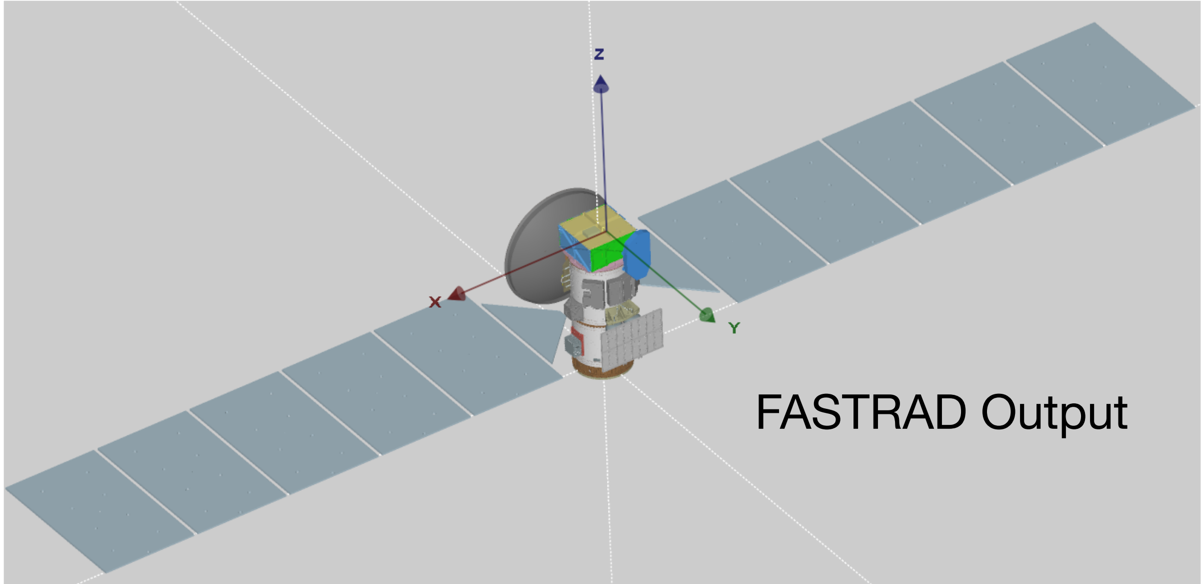
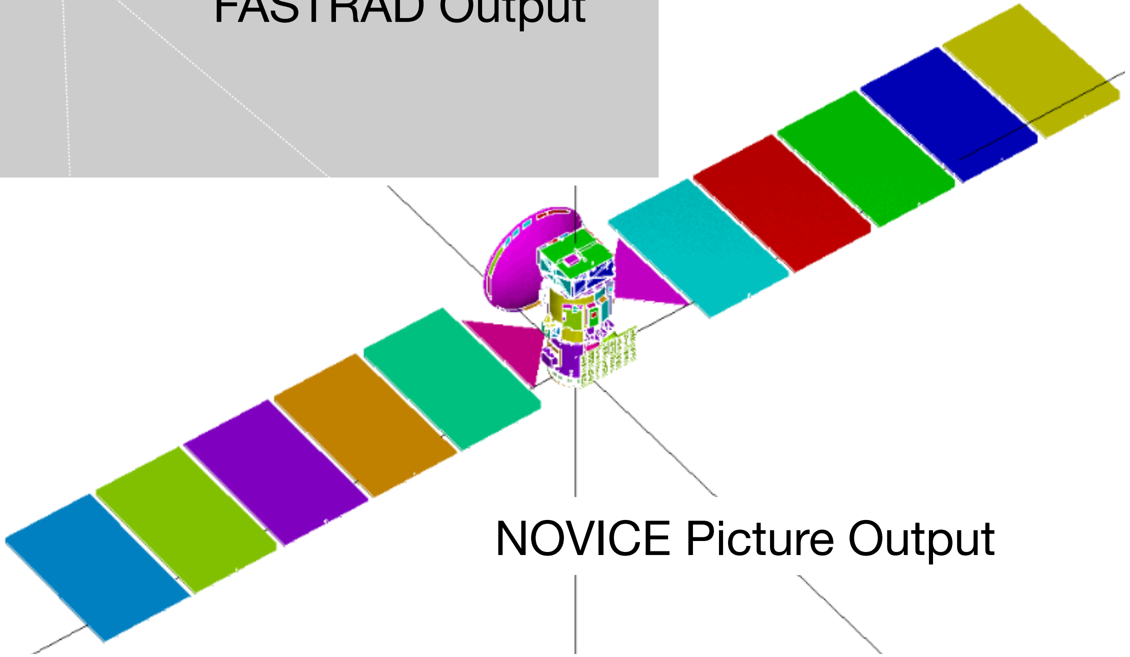
A Jovian Mission Spacecraft Model



FASTRAD Output

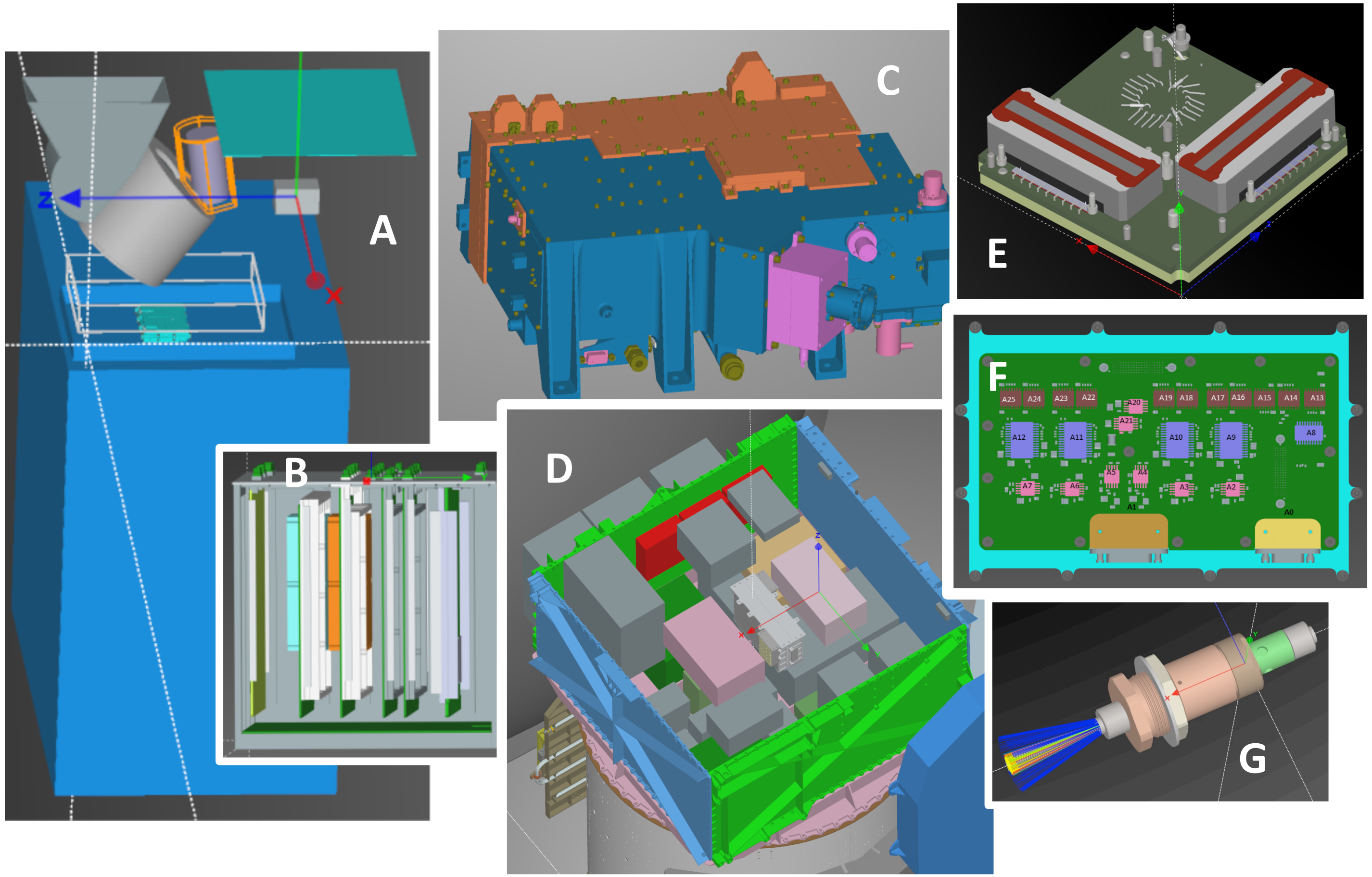


NOVICE Picture Output

- Spacecraft model used in this study is early version released during design optimization phase

Electronics and Instrument CAD Models

-w/ actual materials including high-Z local shields

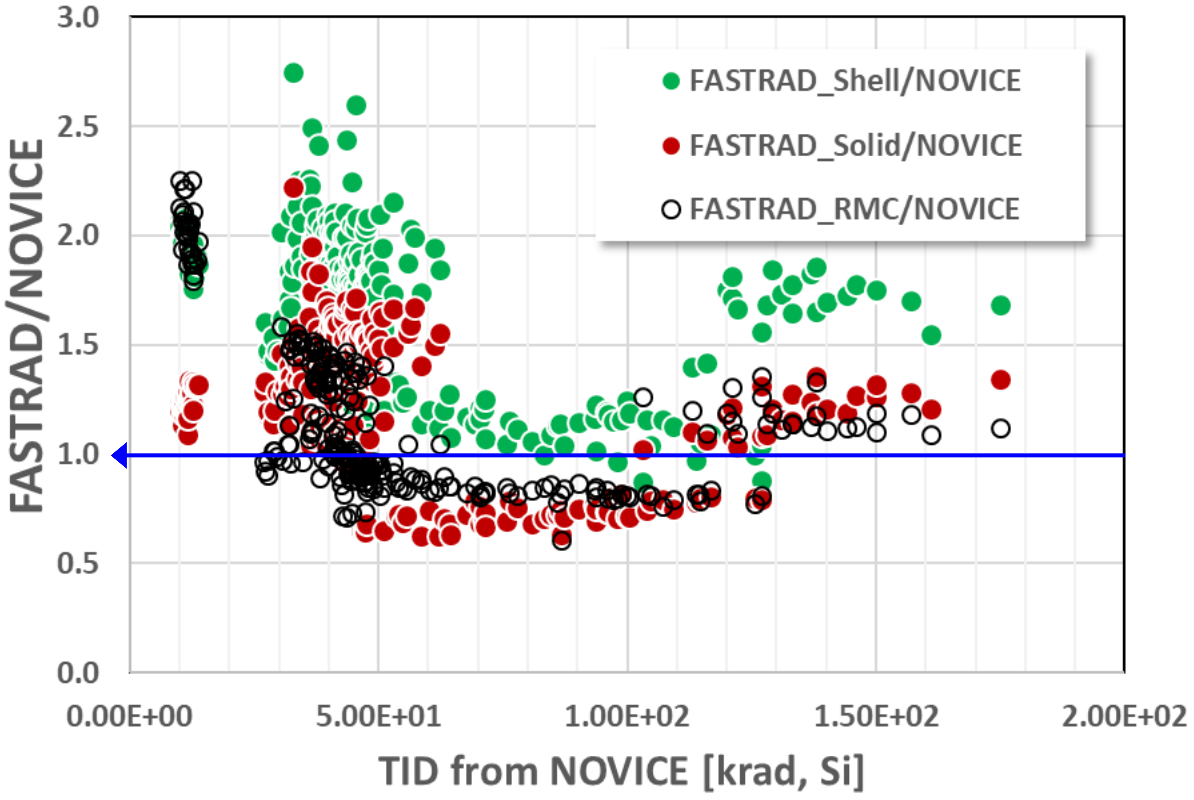


- 311 detector points are surveyed for TID

TID Comparison: Complex Geometries [1/2]

- *FASTRAD vs. NOVICE*

From Deeply Shielded Parts

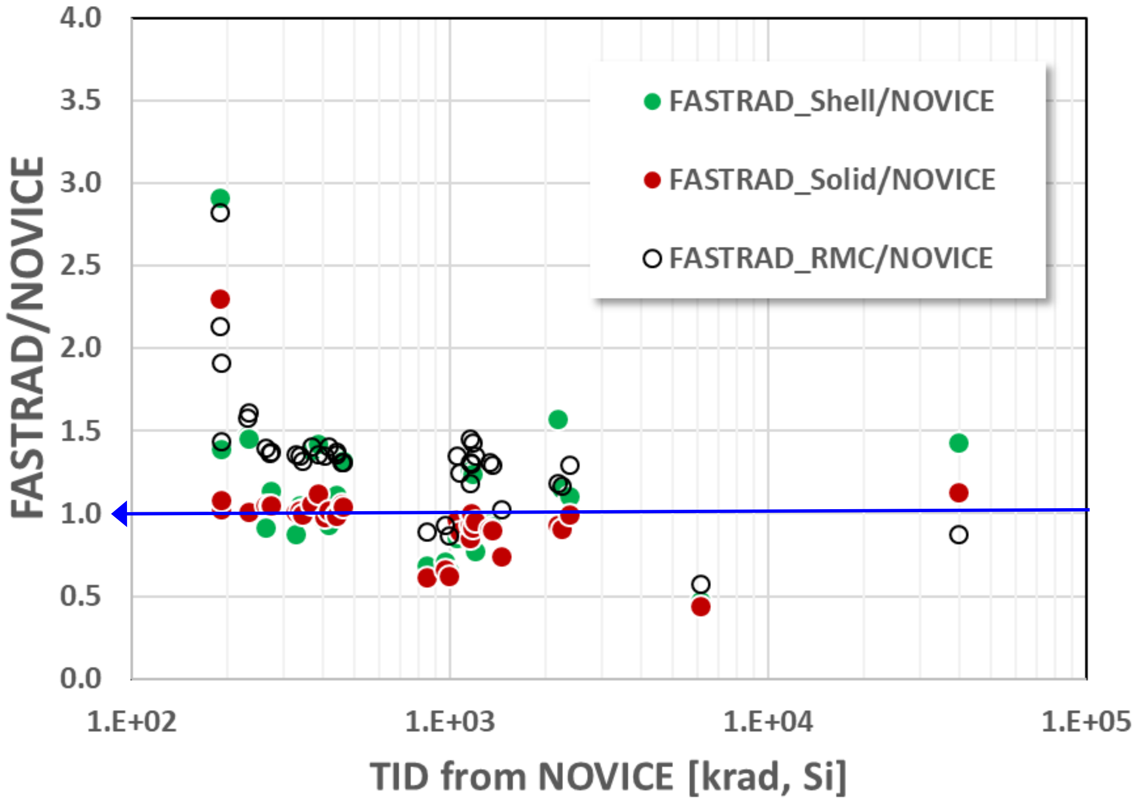


- FASTRAD ray tracing results with shell dose depth curves (DDC) reported in ERD are conservative within run errors
- FASTRAD ray tracing results for solid sphere DDC with slant path calculation are sometimes lower, sometimes higher, than NOVICE results
- FASTRAD RMC results show better agreement with NOVICE for complex geometry cases except heavily shielded geometry giving-TID less than 20 krad

Total Doses from Actual Geometries [2/2]

-*FASTRAD vs. NOVICE*

Marginally to Weakly Shielded Parts



- FASTRAD ray tracing method with shell dose depth curves (DDC) predicts doses similar to, or above, NOVICE dose
- FASTRAD ray tracing with solid sphere DDC/slant path option can under-predict doses
- FASTRAD RMC results show better agreement with NOVICE for complex geometry cases

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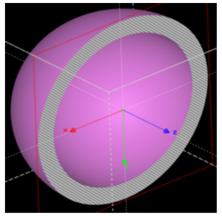
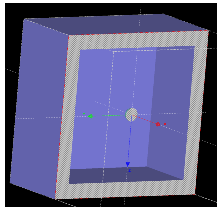
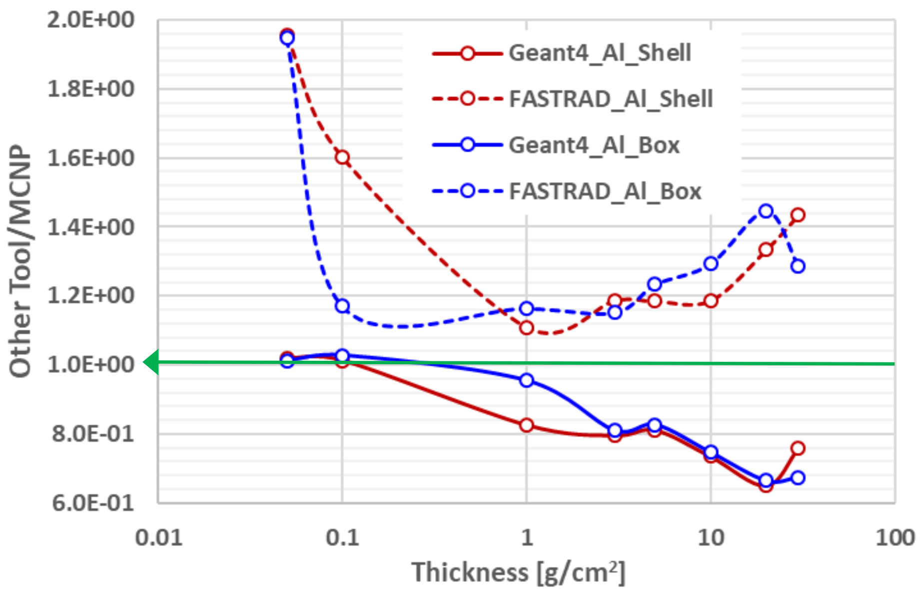
TID Comparison Result [1/2]

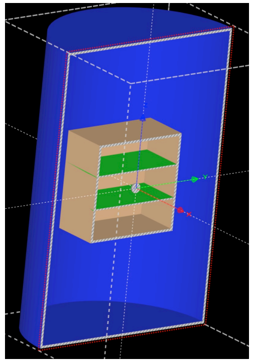
Geant4/FASTRAD_FMC vs. MCNP

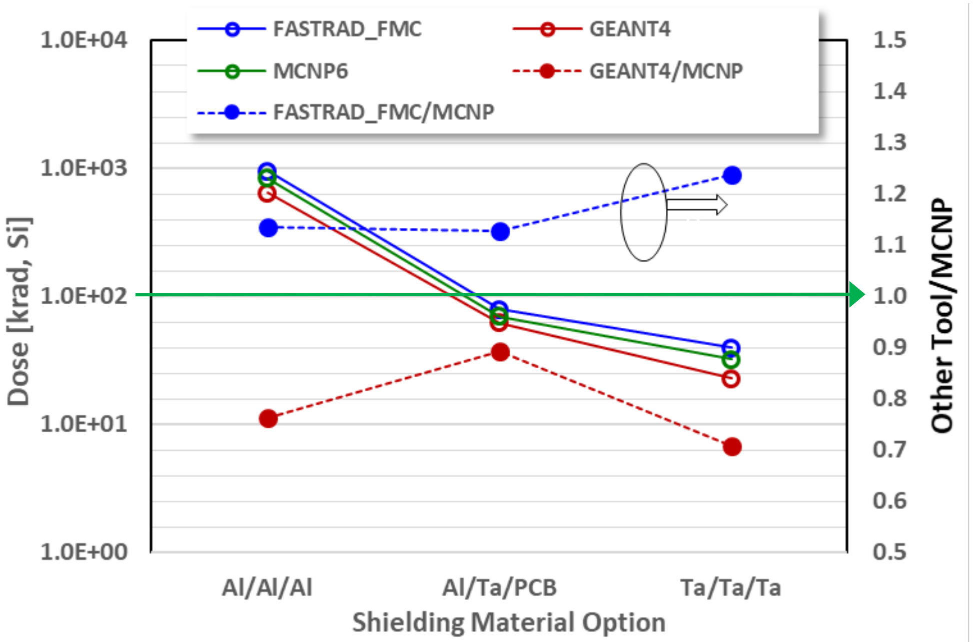




Al Thickness:
0.05 -30 g/cm^2



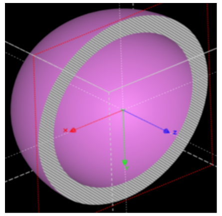




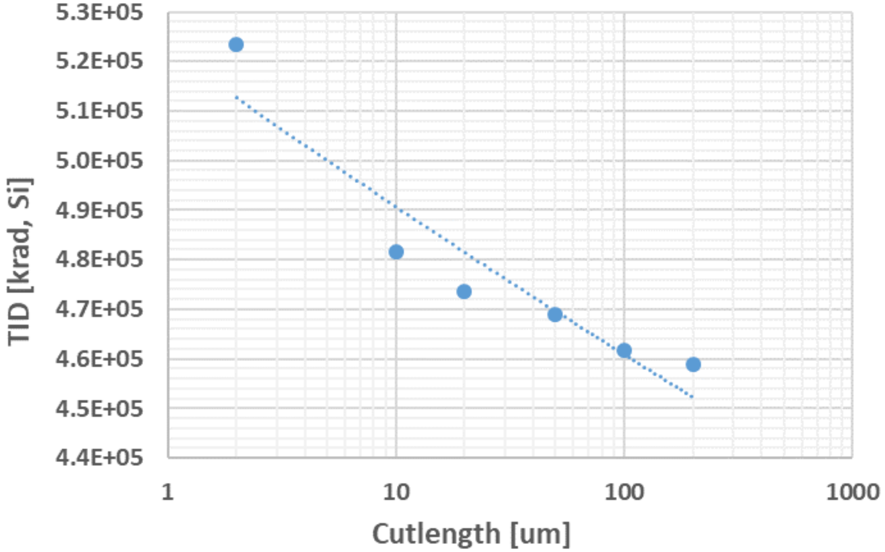
- FASTRAD FMC predicts higher TID than MCNP for all geometries
- Geant4 under predicts doses of shells and boxes as thickness increases
- Geant4 under predicts doses of cylinder vaults for all material combinations

Possible Causes of Discrepancies
-Can it be improved?

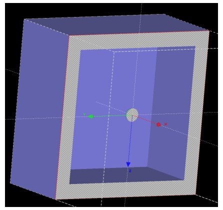
Cut length



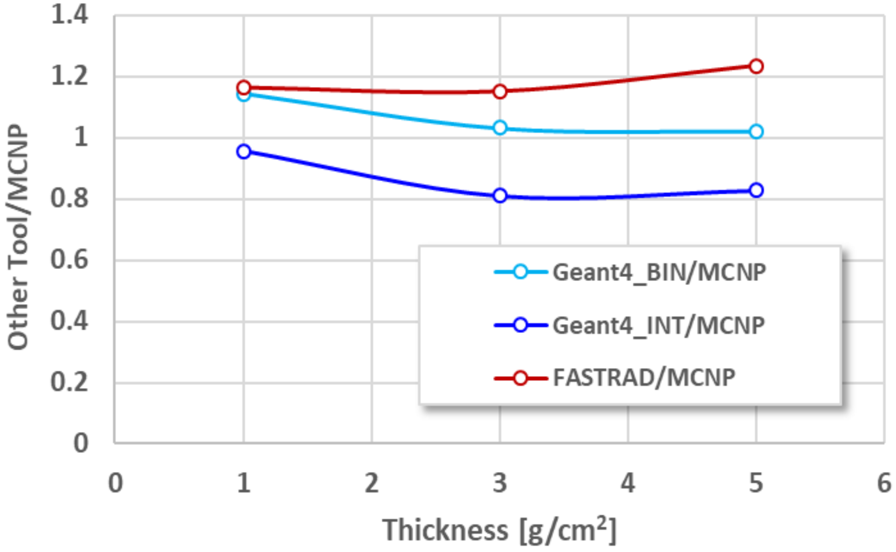
Al Thickness:
3 g/cm²



Energy Spectrum Input Format



Al Thickness:
1 -5 g/cm²



- Energy deposition range cut to be optimized for Geant4 runs
  - With shorter cutlength, TID can be increased by ~10% from the used value of 10 um
- Radiation particle spectrum input format change from integral to BIN affects dose significantly
- It can be further improved by using same physics options for both Geant4 and FASTRAD FMC

Conclusion

- MCNP accepted as foundation
- Novice conservative in comparison with MCNP
  - Except high-Z element / thick shielding combination
- FASTRAD ray tracing favorable for preliminary assessment
- FASTRAD Monte Carlo conservative in comparison with NOVICE
- Geant4 can be comparable with MCNP with optimized run parameters
  - Cut-length, radiation spectrum input format, and etc

Jet Propulsion Laboratory
California Institute of Technology

THANK YOU!

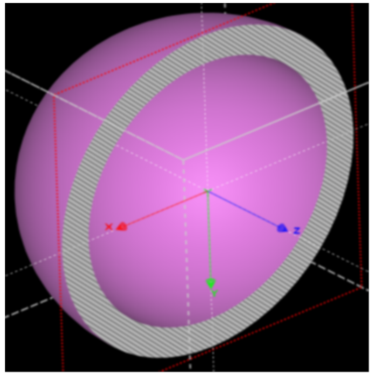
BACKUPs

NOVICE Validation: [3/4]

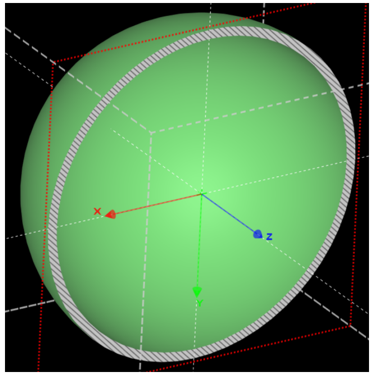
-Is NOVICE Consistent?

1. Geometry/Material

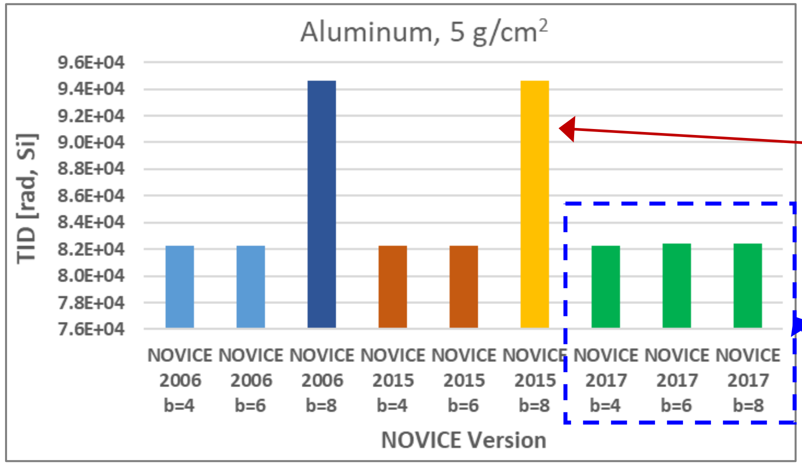
Aluminum: 1 ~ 30 g/cm²

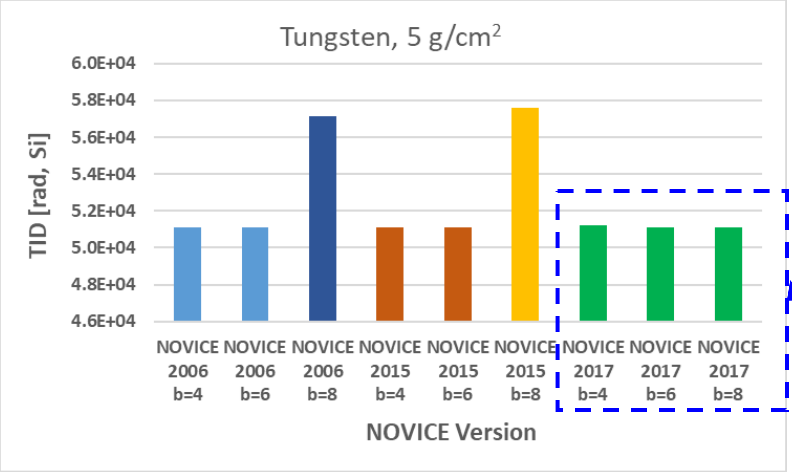


Tungsten: 1 ~ 30 g/cm²



2. TID Results from Multiple NOVICE version/adjoint





3. Discussion

- Outliers from b=8 adjoint options of 2006 and 2015 are due to double counts of secondary electrons in the final dose and it was discovered through NOVICE new version validation

- JPL's current baseline for Europa Clipper TID analysis is NOVICE 2017 adjoint b=8 option
- JPL works closely with the vendor to validate new revisions, prior to insertion to official transport analysis